PRELIMINARY PLANS FOR A CLOSE ENCOUNTER WITH 253 MATHILDE

B. G. Williams, C. L. Helfrich, J. K. Miller, W. M. Owen,
D. J. Scheeres, D. K. Yeomans,

Jet Propulsion Laboratory, California institute of Technology, Pasadena, CA

and

D. W. Dunham, R. W. Farquhar, G. L. Heyler, J. V. McAdams,
S. L. Murchie,

The Johns Hopkins University, Applied Physics Laboratory, Laurel, MD

and

A. P. Harch

Center for Radiophysics and Space Research, Cornell University, Ithaca, NY

AAS/AIAA Space Flight Mechanics Meeting

PRELIMINARY PLANS FOR A CLOSE ENCOUNTER WITH 253 MATHILDE

B. G. Williams, C. E. Helfrich, J. K. Miller, W. M. Owen, D. J. Scheeres, D. K. Yeomans,
Navigation and Flight Mechanics Section, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

and

D. W. Dunham, R. W. Farquhar, G. L. Heyler, J. V. McAdams, S. L. Murchie,
The Johns Hopkins University, Applied Physics Laboratory, Johns Hopkins Road, Laurel, MD 2072.3

and

A. P. Harch
Center for Radiophysics and Space Research, Cornell University, Ithaca, NY 14853

NASA's Near Earth Asteroid Rendezvous (NEAR) mission is planning a close flyby of the asteroid 253 Mathilde in June 1997. The asteroid 253 Mathilde appears to be a distinct and interesting body worthy of further investigation. Unlike the S-class asteroids Gaspra and Ma explored in recent years by Galileo spacecraft flybys, Mathilde is a C-class spectral object and it has a huger diameter of about 61 km. Furthermore, Mathilde appears to have a very slow rotation period, possibly 17 days or longer. The plan is to navigate the NEAR spacecraft to within 1200 km of the center of Mathilde using a combination of NASA's Deep Space Network radio metric tracking and on-board optical imaging. The planned sequence of spacecraft activities will result in high resolution, multi-spectral images of Mathilde made throughout the approach and departure. In addition, the navigation tracking will be used to estimate Mathilde's mass. The mass estimate should be accurate [o about ten percent.

INTRODUCTION

The Near Earth Asteroid Rendezvous (NEAR) mission was the first to be launched in NASA's Discovery Program. The Johns Hopkins University, Applied Physics Laboratory was responsible for designing and building the NEAR spacecraft, and is currently managing and operating the mission [1,2]. Navigation for the spacecraft is being provided by the Jet Propulsion Laboratory, California Institute of Technology 3 The goal of this Discovery mission is to determine the physical and geological properties of the near-Earth asteroid 433 Eros and to infer its elemental and mineralogical composition by placing the NEAR spacecraft and its science instruments into close orbit about the asteroid. Since it is a Discovery class mission, the NEAR project has been developed with a minimum of

staffing, expense and unnecessary complexity. As a result, the spacecraft is simple "in . design with fixed-mounted instruments and solar panels, but it includes advanced capabilities (especially for ease of pointing) that make it easier to operate by a small flight team. This will be described in more detail below for the Mathilde flyby operations.
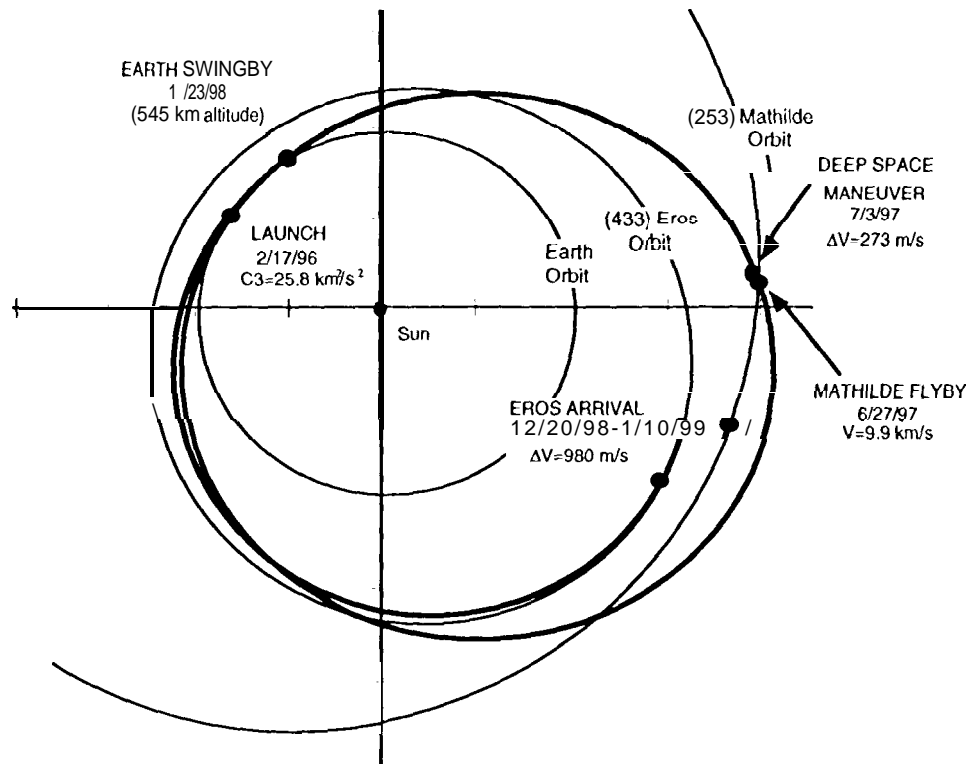

Figure 1 NEAR Trajectory and Mathilde Flyby

NEAR was launched from a Delta-2 rocket February 17, 1996, on a trajectory which takes approximately three years to rendezvous with 433 Eros in December 1998. Events which occur during interplanetary cruise include a flyby of the asteroid 253 Mathilde in June 1997, a deep space maneuver in July 1997, and a gravity assist flyby of the Earth in January 1998 as shown in Figure 1. Planning for the upcoming flyby of Mathilde is the focus of this paper. The flyby is not the primary goal of the mission, but instead is a science target of opportunity on the trajectory taking the NEAR spacecraft to its ultimate goal in 1999, which is to rendezvous with and then orbit 433 Eros. Thus, the planning for the Mathilde encounter assumes the trajectory and approach conditions are constrained to some extent by the overall mission goals to reach Eros. This means that the encounter date and the resulting approach geometry are determined by optimizing the complete trajectory to Eros. Also, the planned spacecraft sequence must not endanger the spacecraft or its instruments. The result is an approach phase angle of over 120 degrees that is not ideal for the first detection of Mathilde with optical navigation since the asteroid will appear as a thin crescent up to the last hours before closest approach (C/A). First detection may be only a couple of days prior to C/A, so independent orbit estimates of

2

Mathilde's ephemeris and the spacecraft trajectory must be made, and the possibility of no optical detection prior to C/A is being planned for as a contingency scenario.

Prior to NEAR launch, the mission and science strategy for the Mathilde flyby was examined in some detail 4 This paper updates that strategy taking into account more recent information about both Mathilde and the operation of the NEAR spacecraft. It gives results of the mission design and navigation trade studies undertaken to plan a navigation scenario of targeting maneuvers and optical navigation images during the last few days before closest approach. This plan of activities will deliver the spacecraft to a point in the B-plane (defined below) to sufficient accuracy so that the multi-spectral imager (MSI) pointing sequence during the closest approach will image Mathilde and not empty space. Additional information about the sequence of spacecraft pointing and MSI operation planned as a result of the flyby timeline and its related delivery uncertainties are discussed below.

Science Goals

Although the asteroid 253 Mathilde was first discovered in 1885, not much was known about it until interest in studying it was renewed with the announcement of the NEAR flyby. Since that time, 1%rth-based observations have determined that it has several unique physical characteristics that make it a good subject for close up study. In recent years, the Galileo spacecraft has made close flybys of the S-class asteroids 951 Gaspra[5] and 243 Ida [6]. However, unlike these objects, Mathilde is a C-class spectral object and it has a larger diameter of about 61 km. Furthermore, Mathilde appears to have a very slow rotation period, possibly 17 days or longer. Mathilde's diameter and photometric characteristics as determined by Tedesco[7] from ground based and IRAS observations arc summarized in Table 1. Since it is inferred from Earth observations, there is uncertainty in the albedo of Mathilde, and this will not be resolved until Mathilde has been imaged in the NEAR flyby. To account for this, the science imaging sequences are planning to use more than one exposure time within a mosaic of images.

Table 1 Physical Characteristics of 253 Mathilde	
Diameter	61 km
Visual Geometric Albedo	0.036
Spectral Type	**C**
Visual Absolute Magnitude (H)	10.3
Photometric Slope Parameter (G)	0.15

The imaging science acquisition goals at the Mathilde flyby are prioritized as follows: (1) partial image of Mathilde at the highest possible resolution in clear filter; (2) complete image of Mathilde at the highest possible resolution in clear filter; (3) complete color image of Mathilde at the highest possible resolution; and (4) images of the region surrounding Mathilde to search for sate]lites or other objects. The radio science goals during the flyby arc to estimate the mass of Mathilde by analyzing the spacecraft radio metric tracking to detect changes in the trajectory after C/A. Another science goal is to combine the mass estimate with a volume estimate (obtained from imaging) to obtain an estimate of the bulk density of Mathilde.

MATHILDE ORBIT ESTIMATE AND UNCERTAINTY

Currently, the orbit estimate of 253 Mathilde is based on some 499 astrometric observation times starting in December 1885 up through July 1996. The July 1996 data represented a large supply of recent, accurate astrometric data from the 1996 opposition of Mathilde. While much of the data were reduced with respect to the Guide Star Catalog, several highly accurate observations were reduced with respect to extragalactic reference star positions. These data were used to predict the orbit and its uncertainty at the time of NEAR's encounter in July 1997. At the time of NEAR encounter, the largest uncertainty component is aligned approximately along the asteroid's orbital path. The ephemeris uncertainty for these data is presented in the next section.

Since the number, quality and data intervals are roughly comparable for asteroids Mathilde, Gaspra and Ida, it is interesting to investigate why the uncertainties for Mathilde are predicted to be more than twice those for Gaspra and Ida. The relatively large ephemeris uncertainties for Mathilde are due to the nearly one year interval prior to encounter when the asteroid will be too close to the sun (as viewed from Earth) for astrometric observations. Just after the 1996 observing season, the ephemeris uncertainties fox Mathilde were comparable to those predicted for Gaspra and Ida during the Galileo encounters (-80 km). However, during the period August 1996 through June 1997 when the asteroid will be unobservable, the ephemeris uncertainties doubled in magnitude. Even if additional observations are assumed in June 1997 when the solar elongation angle will be 40° to 50°, they will not appreciably decrease the uncertainties because they will be taken at large geocentric distances (-2.4 AU). As such, their ability to reduce the orbital errors are limited.

The uncertainty analysis information presented below is given in two reference frames, the so-called RTN and B-plane coordinate systems. The heliocentric RTN coordinate system is defined by a Sun-asteroid unit vector (**R**), a unit vector normal to R and also normal to the asteroid's orbit plane (N) and by a transverse unit vector ('I') that completes the right-handed, orthogonal system such that $T = N \times R$. The uncertainty ellipse is in the orbit plane and oriented with the angle theta which is measured from **R** towards **T**. The B-plane, shown in Figure 2 for the NEAR flyby of Mathilde, is a plane passing through the center of the target body and perpendicular to the incoming asymptote, S, of the hyperbolic flyby trajectory. Coordinates in the plane are given in the R and T directions, with T being parallel to the Earth Mean Ecliptic plane of 2000. The angle θ determines the rotation of the semi-major axis of the error ellipse in the B-plane relative to the T-axis and is measured positive right-handed about S.

Possible Mathilde Ephemeris Improvement

Plans for improving the Mathilde ephemeris include obtaining additional optical astrometric observations planned for June 1997 and radar astrometric data from the upgraded Arecibo planetary radar facility. If the existing astrometric data and planned astrometric observations in June 1997 are combined with radar astrometric data from Arecibo prior to the NEAR encounter, then further improvements to the nominal uncertainties are obtained. These results are presented in Table 2. The timing for obtaining this data and combining it with the other data prior to the NEAR flyby is critical, but if it is obtained and processed in time, it will dramatically reduce the ephemeris uncertainties. While ground-based optical and radar Doppler data taken at about the same time in June

4

1997 also improve the asteroid's ephemeris uncertainties at the spacecraft encounter time, these gains are modest when compared to the power of the range data.
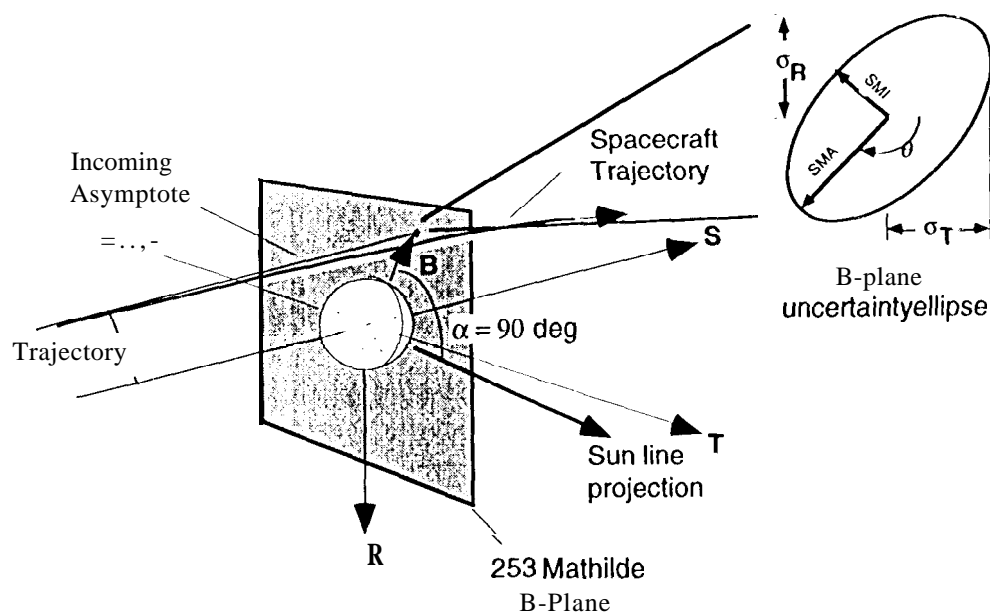

Figure 2 Definition of the Mathilde B-plane

Table 2 Summary of 253 Mathilde Ephemeris Uncertainties at the NEAR flyby. Values represent l-sigma estimates. Under the column heading "1997 Data", the "O", "D", and "R" refer to optical, Doppler, and range data respectively.

RTN Coordinate System:

Orbit Plane Uncertainty Ellipsoid Semi Axes

Case	Data Arc	1997 Data	R (km)	T (km)	N (km)	Major (km)	Minor (km)	Theta (deg)
1	1885-1996	none	31	228	32	228	30	920
2	1885-1997	0	30	204	32	204	30	920
3	1885-1997	O,D	30	199	32	199	30	92°
4	1885-1997	O,D,R	30	76	32	81	19	110°

B-Plane Coordinate System:

B-Plane I. Uncertainty Ellipsoid Semi Axes

Case	Data Arc	1997 Data	T (km)	R (kill)	S (km)	Major (km)	Minor (km)	Theta (deg)
1	1885-1996	none	186	35	134	187	32	1760
2	1885-1997	0	167	35	121	167	32	1760
3	1885-1997	O,D	162	34	118	163	32	1760
4	1885-1997	O,D,R	78	32	27	78	32	0°

Because of Mathilde's relatively large size and slow rotation rate, the upgraded Arecibo planetary radar, which is expected to resume operation during the Spring of 1997, should be able to provide both Doppler and delay (range) measurements in late May and June of 1997. The benefit of processing these data are noted in Table 2. Since the relative flyby velocity is approximately 10 km/s, the use of radar range data in the pre-encounter orbit/ephemeris development could reduce the time-of-flight uncertainty (due to Mathilde alone) down from 12 seconds to 3 seconds. Plans are being made incorporate this data into (he flyby operations if it is available; this is included as one of the possible scenarios in the navigation case studies shown below.

NAVIGATION TO MATHILDE

The navigation timeline is shown in Table 3. This catalogs the events important to navigation around the Mathilde flyby. This timeline identifies the three remaining trajectory correction maneuvers (TCMs) planned to re-target the NEAR trajectory to the desired aim point. The statistical magnitudes of these maneuvers are presented in a following section and are based on the orbit determination performance expected as NEAR approaches Mathilde. Note that the targeting maneuver (TCM-6) at fifteen days prior to closest approach will be based on the best estimate of the NEAR trajectory and the best a priori asteroid ephemeris knowledge at that time, since it occurs well before the first on-board optical detection of 253 Mathilde. The final maneuver (TCM-7) is a contingency to correct possible errors from the first burn and to respond to the improved relative position information available after optical navigation data has been obtained. This technique has been used successfully during navigation of the Galileo Gaspra and Ida asteroid encounters [8,9] to incorporate new trajectory knowledge as it is acquired rather than waiting until the last moment for a single attempt to retarget. The placement of optical navigation pictures and TCMS has been iterated between the mission design, science, navigation, and spacecraft engineering teams to operate within constraints throughout the encounter.

Navigation Uncertainty Analysis

Using measured MSI performance and predicted visibility of Mathilde, the first detection may not occur until less than two days before the closest approach. Before this first detection, the spacecraft trajectory is targeted by a propulsive maneuver to flyby the location of Mathilde predicted by its ground-based ephemeris. Orbit determination analyses for three different navigation scenarios were considered. The first, referred to as the nominal, simulates the flyby without radar observations to improve the ephemeris, but with optical navigation pictures. The second scenario simulates a flyby without Opnav pictures, but with a much improved Mathilde ephemeris due to Arecibo radar observations. The final scenario assumes no Opnav ant] no radar improvements to Mathilde's ephemeris were made. The results of this analysis are presented together with the statistical maneuver results in the next section in Table 5.

As NEAR approaches Mathilde, the statistical error in the location of the B-plane target point will be increased slightly after each TCM due to errors in the burn. This is the control uncertainty. Before and a short time after each TCM, orbit determination will estimate the location of the target point with an associated uncertainty. This is the knowledge uncertainty. The first type of error indicates how well the trajectory can be targeted, and the second indicates how well the actual flyby trajectory can be determined after the targeting maneuvers are performed, B-plane error ellipses and linearized time of

Table 3 NEAR Navigation Timeline for Mathilde Flyby

Date in 1997	Event Description (TCM=trajectory control maneuver)		
April 23	Spacecraft Pointing and Imaging Sequence Test		
May 21	TCM-5		
late May, early June	Optical and Radar updates to Mathilde ephemeris		
June 12	Opnav Demonstration (-50 deg off-sun pointing demo w/ pictures)		
June 20	TCM-6		
June 21	Orbit Update to MSI Planning and Onboard Ephemeris		

June close encounter timeline:

Time before closest approach (C/A)		Apparent mag(Albedo=0.04)		
	CIA-42 h	Opnav 1	7.9	-8.9
	C/A-36 h	Opnav 2	7.7	-8.7
	C/A-30 h	Opnav 3	7.4	-8.4
	CIA-24 h (data cutoff for TCM-7)	Opnav 4	6.9	-7.9
	C/A -12 h	TCM-7		
	C/A-n h	Opnav 5 (Last Opnav Picture)	6.3	-7.3
	CIA -5 h	Upload of last update to Ephemeris based on C/A -11 h Opnav		
June 27	C/A	MATHILDE FLYBY		
July 3	TCM-8	Deep Space Maneuver		
July 2 3	TCM-9	Cleanup Maneuver		

flight (LTF) uncertainties for the nominal scenario are shown in Figure 3 for both these types of error. The ellipses are all drawn with their centers at the nominal aim point, but in reality the actual trajectory after TCM-7 will lie somewhere within the 1 -σ ellipse with probability 68%. The knowledge ellipses numbered 3 and 4 in the Figure represent the uncertainty in the determination of the post TCM-7 target, and after the fact they could be centered about the estimated aim point. As shown in Table 3, this final knowledge will be uplinked to the spacecraft as an update to the relative on-board ephemeris so that imager pointing during the flyby will be based on this last best estimate. This will be explained further in the following section on spacecraft considerations.

To obtain these values the navigation team assumed knowledge of the spacecraft attitude accurate to -10 to properly calibrate the solar pressure acceleration and its effect on both the trajectory and the DSN Doppler tracking. To accurately measure and constrain the NEAR solar radiation pressure model coefficient, weekly range passes have been scheduled up to the time of Mathilde flyby. These also strengthen the trajectory solution which will be degraded locally due to a zero declination condition in April 1997 and solar conjunction in February 1997.

Impact of Spacecraft Ranging on Mathilde Flyby Uncertainties

It is estimated that one full pass of DSN range measurements once a week starting in April will enable NEAR navigation team to accurately measure and re-estimate the solar radiation pressure coefficient of the spacecraft in support of the Mathilde flyby. It is important that these range passes be taken from both Canberra and from either Madrid or Goldstone, so that the north-south baseline breaks the near singular observing geometry during the low declination passes in April 1997. The effect of the DSN ranging is shown in Table 4 for both a worst case simulation that included unknown spacecraft non-gravitational accelerations at a few nanometers per second per second+, and a best case where these accelerations were not included.

Table 4 Predicted Mathilde B-Plane orbit determination knowledge uncertainties with a data cut-off 12 hours prior to flyby

Comments	σ_a (km)	σ_b (km)	θ (deg)	σ_T (see)
No S/C ranging (use as worst-case)	20.5	20.3	127.9	21.8
Worst-case with *SJC* ranging	21.0	20.4	83.4	11.6
Best-case with S/C ranging	21.5	20.4	80.5	5.6

Description of Targeting Maneuvers

The design parameters for all the approach trajectory correction maneuvers (TCMs) are the impact plane (or B-plane) conditions of the asteroid given in a target relative coordinate system. This has been true of all maneuvers since launch where the miss distance at Mathilde has been steadily decreased from over 800,000 km to the current value of about 1,200 km with each successive maneuver 3

For the error analysis here, the observed maneuver execution errors from recent NEAR trajectory correction maneuvers were used. These resulted in fixed magnitude errors of 2 mm/s with an additional proportional magnitude error of 2%. For pointing error models, a fixed pointing error of 2.1 mm/s per axis and a proportional pointing error of 3 milliradians per axis are used. All these error assumptions are for one standard deviation (1-a). The three different navigation scenarios used in the orbit determination analyses were used in a monte carlo analysis to determine the maneuver control statistics. In each sample run, TCM-7 was assumed to use critical plane targeting in which the encounter time was not corrected back to a specific flyby time. The results for these cases along with the orbit determination results are shown in Table 5. No(c that as mentioned above, the case with the improved Mathilde ephemeris due to Arecibo ranging has about a three second uncertainty in flyby time and also the smallest statistical maneuver costs.

The monte carlo analysis was repeated with sample runs where TCM-7 corrects both back to the aim point and to a chosen flyby time. In this case, the statistical maneuvers were slightly huger than those for the critical plane targeting cases above, and

---

[1] This could be caused by outgassing or by mismodeling of the solar radiation pressure; e.g., uncertainty in spacecraft pointing.

[he uncertainty in the linearized time of flight was smaller. All the other maneuver control statistics were unchanged. These results for the mean maneuver magnitude and standard deviation along with the improved LTF statistics arc shown in Table 6.

'I'able 5 Orbit Determination Knowledge and Statistical Maneuver Control Results for Planned Maneuvers

Nominal Scenario Without Mathilde Ranging but with Opnav

	Statistical Maneuver		Maneuver Control Statistics			O.D. Knowledge Statistics		
	A V (m/s)	σ(m/s)	σB•T (km)	σB•R (km)	σLTF (s)	σB•T (km)	σB•R (km)	σLTF (s)
TCM-5 (May 21)	0.088	0.046	238	166	12.9	233	166	12.9
TCM-6 (June '20)	0.61	0.33	180	156	12.6	179	156	12.6
TCM-7 (June 27)	4.75	2.62	35.8	30.4	12.4	35.8	29.3	5.9

Scenario Two - V th Mathilde Ranging, but wit out any Opnav

	Statistical Maneuver		Maneuver Control Statistics			O.D. Knowledge Statistics		
	A V (m/s)	σ(m/s)	σB•T (km)	σB•R (km)	σLTF (S)	σB•T (km)	σB•R (km)	σLTF (s)
TCM-5 (May 21)	0.088	0.046	238	166	12.9	233	166	12.9
TCM-6 (June 20)	0.55	0.30	170	176	4.0	170	77	4.0
TCM-7 (June 27)	4.33	2.52	98.3	75.8	3.9	98.3	73.8	3.2

Scenario Three - W hout Mathilde Ranging, and w thout any Opnav

	Statistical Maneuver		Maneuver Control Statistics			O.D. Knowledge Statistics		
	A V (m/s)	σ(m/s)	σB•T (km)	σB•R (km)	σLTF (s)	σB•T (km)	σB•R (km)	σLTF (s)
TCM-5 (May 21)	0.088	0.046	238	166	12.9	233	166	12.9
TCM-6 (June 20)	0.61	0.33	180	156	12.6	179	156	12.6
TCM-7 (June 27)	5.98	3.37	112.1	156.9	12.4	112.1	154.2	12.4

9

	Statistical Maneuver		Control Statistics
Table 6 TCM-7 Statistical Maneuver Control to a Chosen Flyby Time[‡].			
	AV (ill/S)	σ(m/s)	σLTF (s)
Nominal	5.60	2.84	5.9
Scenario 2	4.47	2.53	3.2
Scenario 3	7.01	3.82	12.4

The statistical magnitudes of TCM-6 and TCM-7 were used to plan thruster usage and realistic spacecraft maneuver sequences to check for pointing constraints. It was assumed that the spacecraft would be pointing its high gain antenna at Earth (17.9° from the B-plane normal) and that the ΔV would be at the worst angle (for solar array pointing, and thus power) in the B-plane. 'I'his results in an additional 1.05 penalty factor in the ΔV magnitudes from an unconstrained case. In addition, the expected ΔV for TCM-7 is being used with the pointing constraints to plan ahead which thrusters will be selected. If the B-plane error turns out to be 50 km or less, there would be little point in doing TCM-7, since this results in a 2.5° difference in the maximum Sun angle occurring during the flyby from the 90° nominal aim point, and the imaging sequence is robust enough to deal with that level of error. Also, this level of error would result in less than 0.2° difference in the Sun angle on the spacecraft solar arrays, which is negligible.

SPACECRAFT CONSII)ERATIONS

Pointing and Sequence Capabilities

As a Discovery spacecraft, NEAR was designed with fixed-mounted instruments and solar panels for low-cost and reliability. This normally would have increased the workload of planning and operations personnel, but it was also designed with advanced guidance and control (G&C) capabilities (especially for case of pointing) that makes it easier to operate by a small flight team. These capabil it ies and their impact on the Mathilde flyby planning are described here.

'I'he multi-spectral imager used for science and Opnav is rigidly fixed to the spacecraft and its boresight is nominally aligned with the spacecraft x-prime axis. The spacecraft guidance and control (G&C) system is responsible, therefore, for maneuvering the entire spacecraft through a prescribed time-varying attitude and rate profile to collect the desired scientific data and Opnavs. To accomplish this, the guidance portion of the G&C system utilizes current spacecraft position and velocity, an object position and velocity, and a roll orientation (around the x-prime axis) to compute the instantaneous seven-clcmcnt attitude state at a 20 Ilz rate. Both spacecraft and asteroid orbits arc uplinked in the form of Chebyshcv polynomials, and decoded in real-time to produce the instantaneous position and velocity values. The spacecraft orbit can be defined in either an SCI (sun centered inertial) or an ACI (asteroid centered inertial) coordinate system, where 'inertial' implies the J2000 earth equator coordinate system. The asteroid orbit is always defined in the SCI coordinate system.

---

‡ The scenario numbers refer to those in Table 5.

Given the spacecraft and asteroid orbits and a small amount of additional information, NEAR can be commanded to point and maintain imager track on static or moving object locations defined in at least four different methods: (a) Inertial unit vectors - used for pointing imagers at star fields for calibration purposes; (b) ACI relative position - used for looking at non-rotating regions near' the asteroid; (c) Off-nadir angles - elevation and azimuth angles relative to nadir direction (to asteroid center); and (d) Surface fixed position - used at Eros to point at specific surveyed landmarks. Each of the four methods can optional1 y invoke a scan pattern which imposes a t i me-dependent object motion relative to its initial input value. These motions can take the form of linear, raster, sawtooth, or great-arc scan patterns. Examples include: motion of a star across an imager's focal plane for calibration purposes, and motion through various asteroid surface locations to build up organized mosaics, as is planned for use on the Mathilde flyby.

The Mathilde encounter sequence will use a spacecraft orbit expressed in ACI coordinates, meaning the uplinked orbit will be derived using a time-history of NEAR's positions relative to the center of Mathilde. An off-nadir angle pointing scenario will be used such that the imager boresights will maintain pointing at or near nadir during the 10 km/sec 1200 km closest approach flyby. Uncertainty in the precise location of Mathilde during the flyby leads to a elongated sphere of uncertainty that is larger than Mathilde. This will be discussed further in the section on Science Data Collection plans below. To guarantee that images of the asteroid are obtained, the imager foresights cannot simply be pointed at nadir, but will be scanned across the long axis of the sphere of uncertainty several times during the flyby. This scan pattern will be implemented by smoothly varying the off-nadir azimuth and elevation angles in a desired fashion. Based on predicted navigation errors, the off-nadir pointing angle needed to encompass the two-sigma sphere of uncertainty is expected to be less than six degrees.

Pre-Flyby Pointing and Sequencing Tests

To demonstrate spacecraft performance anti capability to handle the high-rate slew, a preliminary version of the Mathilde flyby scenario, including scan patterns, was uplinked and executed on the spacecraft in September 1996. With the help of two uplinked simulated orbits, the spacecraft underwent the actual attitude maneuvers that w ill be used for the flyby. To maintain NEAR's knowledge of the position of the sun at all times, the spacecraft's sun-centered orbit was uplinked as the simulated asteroid orbit, and a new spacecraft asteroid relative orbit, spanning a few dozen minutes, was upl inked to define the simulated flyby. At the end of the experiment, the actual spacecraft sun-centered orbit was again loaded. This test was repeated on January 15, 1997 and another is planned for April 2.3, 1997. These simulations help test the actual response times and performance of NEAR's G&C algorithms while also providing a check on flight team procedures and interfaces.

The results of these tests to date indicate the spacecraft G&C system is working as designed and the MSI and its software are being calibrated and validated. In one part of the tests, eight images of the star Canopus were taken 1 second apart and compressed. The 8 fast Canopus images show essentially no evidence of spacecraft jitter, as it was much less than one pixel over 8 seconds. Two of the frames had strong cosmic ray hits, but the strategy at Mathilde will be to take multiple images over short periods of time to avoid loss of i nformat ion (especially on Opnavs). All the Canopus images were. acquired at the

commanded time even when compression was used on 8 images commanded to be .
acquired 1 sec apart.

SCIENCE DATA COLLEC'1'1ON PLANS

MSI Sequencing Plans

The imager science goals for Mathilde will be attempted within the guidelines set by the NEAR project and the spacecraft capabilities. The fastest image acquisition will be one image every two seconds. The uncertainty in albedo of Mathilde will make multiple exposures necessary and will limit the slew rates used. The slew rate will be planned to maximize the rate of coverage, yet it will keep the smear less than or equal to one-half pixel for 1000 dn (with exposure times calculated assuming nominal albedo). This way, a second exposure (assuming twice nominal albedo) will still keep smear less than or equal to one pixel.

The imaging sequence consists of five types of mosaics (plus a satellite search) that arc planned throughout the flyby interval. Each sequence has specific objectives; their placement during the flyby and their expected resolution arc shown in Table 7. The first sequence is called the 'high phase image' in Table 7, and it consists of a series of 21 clear filter images taken three at a time at positions spaced ten seconds apart beginning 4m50s and extending to 3m before closest approach. This mosaic, like the others here, is planned to cover most of the 2-sigma error ellipsoid and thus presents a 90% probability of returning images of at least half of Mathilde. The 'highest resolution partial image' sequence consists of a series of 40 clear filter images taken two at a time at positions spaced two seconds apart beginning 1 m 10s before closest approach to 1 m 10s after. The resolution expected during the nominal flyby (at 1200 km from the center of Mathilde) will be about 219 m/pixel (183 m/pixel at C/A). A 'pixel' here is defined as the short length of the MS] rectangular CCD element, thus it is equivalent to about 161 µrad in the MSI field of view.

The third type of mosaic, similar to the previous one, is called the 'high resolution partial image' in Table **7,** and it is a series of 34 images taken two at a time at positions spaced six seconds apart that begin 1 m 10s after C/A and end 2m52s after. The resolution expected from this mosaic will be from 219 to 331 m/pixel. A global mosaic image will be attempted starting at 2m52s after C/A and will extend up to 3m49s after. This mosaic is called the 'global image' and is made up of 30 total images taken two at a time at positions spaced four seconds apart. The first multi-spectra] mosaic acquires a six filter set of images at nominal exposures, then another set of six using a second set of exposures. These both arc repeated every 32 s for five sets of twelve, or a total of 72 images in the first set. The second multi-spectral mosaic will slew to the center of the uncertainly region and hold. "1'here the MS] will acquire an eight filter set of images, two exposures for each filter, every 48 seconds for a total of about 42 images. The satellite search plans to acquire sets of 10 clear filter images with 1 second exposures where these sets arc repeated every 5 minutes. This will result in about 30 total images.

Table 7 Imager Sequences Planned for Mathilde Flyby

Observation	Timing Relative to C/A	Number of Images	Most Probable Phase Angle (deg)	Most Probable Resolution (m/161μrad)
High Phase Image	-5m20s to -3m	21	**134**	**455**
Highest Res. Partial Image	-1m10s to +1m10s	40	91	183
High Res. Partial Image	+1m10s to +2m52s	34	55	293
Global Image	+2m52s to +3m49s	20	49	374
Multi-spectral Image (I)	+3m49s to +6m9s	72	45	549
Multi-spectral Image (II)	+6m30s to +8m18s	'42	42	650-820
Satellite Search	+1 Om to +20m	30	41	976-1926
Image Total=		2S9		

Three sequence scenarios are being evaluated for planning purposes. They are: (1) the 'nominal' sequence which is based on a 1200 km miss distance, 90" inclination, and the uncertainties associated with a C/A -24 h Opnav. This assumes completion of TCM-7, which is based on the C/A -24 h Opnav; (2) a contingency sequence designed for the 1200 km miss distance, 90" inclination, and the uncertainties associated with a 'late update' -11 h Opnav. This also assumes completion of TCM-7, which is based on the -24 h Opnav; and (3) a contingency sequence designed for the 1200 km miss distance, at 90° inclination, which assumes no Opnavs are acquired and TCM-7 is not performed. Trajectories that are perturbed from the nominal, based on calculated navigation uncertainties, are currently being used to validate the robustness of the overall sequence design.

The MSI science team is continuing to evaluate the science benefit or loss associated with changing the nominal miss distance from 1200 km to something greater (1300, or 1400 km). The NEAR project will evaluate the engineering arguments for or against changing the miss distance and a final target wi ll be chosen before TCM-5.

Plans for Mathilde Mass Estimate

There are three main constraints on the flyby conditions which will affect the ability to determine the asteroid mass. These are the flyby radius, the amount of continuous tracking available around the flyby and the amount of tracking lost during closest approach to satisfy science imaging requirements. An analysis was performed for the flyby radius of

13

1,2.00 km. to determine the expected accuracy of the Mathilde mass estimate. The mass of ,
Mathilde was computed using a density of 2.6 g/cm^3 and a radius of 30.5 km, leading to a
mass parameter of $\mu = 0.0206\ \text{km}^3/\text{s}^2$. The covariance analysis further assumed both TCM-
6 and TCM-7 were performed as planned (o an accuracy of 1 mm/sec. The remaining
parameters of interest arc given in Table 8:

Table 8 Filter Parameters Used in Mathilde Mass Estimate Covariance Analysis

Doppler Data Accuracy	0.1 mm/sec (60-second count time) for X-Band Doppler
Optical Navigation Accuracy	80 μradians
Estimated Parameters	S/C State, Solar Radiation Pressure, Maneuvers, Stochastic Process Noise, Asteroid Ephemeris, Asteroid Mass
Error Effects Considered	Station Location Uncertainties, S/C Orientation Uncertainties, Earth Timing Uncertainties, Tropospheric Effects, Ionospheric Effects

---

Three results are shown in Figure 3 for the nominal flyby at 1,200 km radius. The
first of these labeled 'Data limit uncertainty' is the idealized uncertainty based on data noise
without including the effect of the consider parameters (listed in Table 8). The uncertainties
in the consider parameters arc included in the filter, but they are not estimated, so as to
model the effect of the systematic errors in the tracking data on the mass estimate. It was
found that tracking the spacecraft for longer than 3 days after closest approach did not yield
significant improvement in the estimated mass.

Since DSN tracking during the hour on either side of closest approach is not
avai lable, the filter must estimate the prc and post flyby velocity vectors to infer the
delivered AV from the flyby and, in turn, determine the mass from this estimate. To do
this the spacecraft should be tracked continuously from ±3 days to closest approach. It is
crucial that the spacecraft be tracked continuously for at least 3 days following closest
approach. This should be sufficient information to estimate the mass to within 10% of its
actual value.

CONCI.US1ONS

The NEAR mission operations, navigation, and science teams will be training for
real time operations and performing simulation tests both on the ground and with the
spacecraft prior to the Mathilde flyby on June 27, 1997. These activities are aimed at
maximizing the potential science return from the flyby while ensuring safe operation of the
spacecraft. Both imaging science and radio science expect to return important information
about this asteroid. The multi-spectral imager sequences are being designed for three
possible scenarios in order to anticipate the most probable events that will actually occur
during the flyby. The nominal, or most likely, case assumes that a final targeting maneuver
occurs at closest approach (C/A) minus 12 h and a pointing update is uplinked based on an
optical navigation image at C/A minus 11 h. For this case, the NEAR multi-spectral imager
should return images with resolution as good as 183 m per pixel at closest approach with a

probability of 90%. The radio science planning includes scheduling of DSN Doppler and range data which should insure an estimate of Mathilde's mass to ten percent uncertainty.

In planning for the flyby, the navigation knowledge and control uncertainties needed to deliver the spacecraft to the B-plane target have been estimated based on scheduled tracking of the spacecraft and on the uncertainties in the Mathilde ephemeris. There is a probable improvement in the Mathilde ephemeris due to Earth-based optical astrometric observations in late-May to early-June of 1997. The possibility also exists for a much improved ephemeris if radar astrometric data can be obtained from the upgraded Arecibo planetary radar facility prior to the flyby. The knowledge and control uncertainties for navigation under each of these scenarios has been analyzed, and the flyby operational timeline and procedures are allowing for each possibility.

The current flyby target is set at 1,200 km from the center of Mathilde at 90° from the projection of the Sun line in the B-plane (in the Northern Ecliptic hemisphere). Even though this flyby is not the main goal of the mission, it will benefit both calibration of the spacecraft and validation of team procedures. In addition, the Mathilde flyby provides the possibility of unique science returns while on the way to NEAR's rendezvous with the asteroid Eros in December 1998.
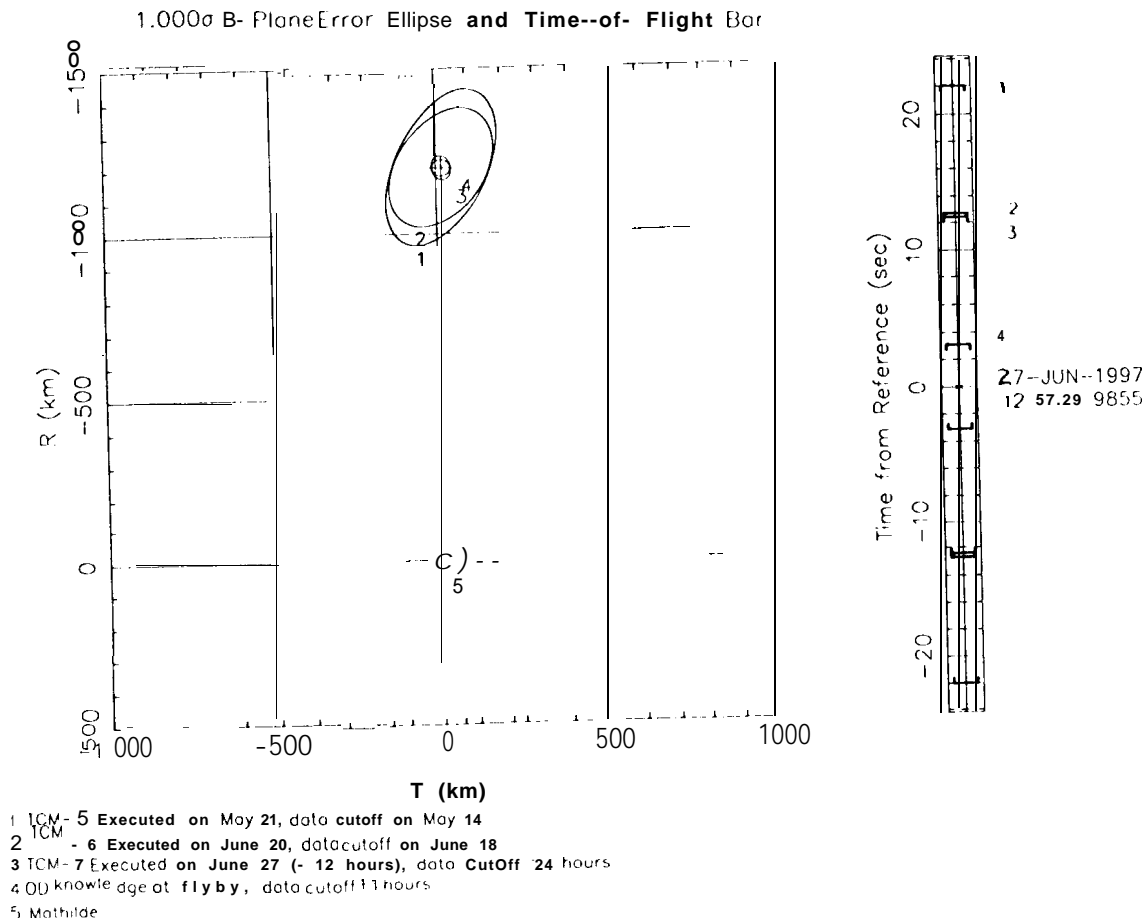
ACKNOWLEDGMENTS

REFERENCES

1 Farquhar, R. W., Dunham, D. W., and McAdams, J. V., "NEAR Mission Overview and Trajectory Design," *J. Astron. Sciences*, Vol 43, No 4, Oct.-Ike. 1995, pp. 353-371.

2 Landshof, J. A. and Cheng, A. F., "NEAR Mission and Science Operations," *J. Astron. Sciences*, Vol 43, No 4, Oct.-Dec. 1995, pp. 477-489.

3. Harch, A. P., D. W. Dunham, R. W. Farquhar, J. Veverka, B. G. Williams, and D. K. Yeomans, "Encounter Strategy for a Flyby of the Main-Belt Asteroid 253 Mathilde," *J. Astron. Sciences*, Vol. 43, No. 4, Oct.-Dec. 1995 pp. 399-415.

4, Veverka, J., M.J.S. Belton, K. J'. Klaasen, and C. R. Chapman, 'Galileo's Encounter with 951 Gaspra: Overview," *Icarus*, Vol. 107, 1994, pp. 2-17.

5 Belton, M. J. S., C. R. Chapman, K. P. Klaasen, A. P. Harch, P. C. Thomas, J. Veverka, A. S. McEwen, and R. 'I'. Pappalardo, "Galileo's Encounter with 243 Ida: An Overview of the Imaging Experiment," *Icarus*, in press.

6 Tedesco, E. F., "Magnitudes, UB V Colors, and J RAS Albedos and Diameters," in *Asteroids II*, Binzel, R., Gehrels, T. and Matthews, M. S. (editors), University of Arizona Press, Tuscon, 1989, pp. 1090-1161.

7. Kallemeyn, P. H., R. J. Haw, V. M. Pollmeier, and F. 1. Nicholson, "Galileo Orbit Determination for the Gaspra Asteroid Encounter", paper AIAA 92-4523, AIAA/AAS Astrodynamics Specialist Conference, Hilton Head, SC, August 10-12, 1992.

8. Antreasian, P. G., F. 1. Nicholson, P. H. Kallemeyn, S. Bhaskaran, R. J. Haw, and P. Halamek, "Galileo Orbit Determination for the Ida Encounter", paper AAS 94-132, AAS/AIAA Space flight Mechanics Meeting, Cocoa Beach, FL, February 14-16, 1994.

9. Williams, B. G., J. K. Miller, D. J. Scheeres, C. E. Helfrich, T. C. Wang, W. M. Owen, and G. D. Lewis, "Navigation Results for NASA's Near Earth Asteroid Rendezvous Mission", paper AIAA 96-3579, AIAA/AAS Astrodynamics Specialist Conference, San Diego, CA, July 29-31, 1996.

1.000σ B- Plane Error Ellipse and Time--of- Flight Bar

1 TCM - 5 Executed on May 21, data cutoff on May 14
2 TCM - 6 Executed on June 20, data cutoff on June 18
3 TCM - 7 Executed on June 27 (- 12 hours), data Cutoff 24 hours
4 OD knowledge at flyby, data cutoff 11 hours
5 Mathilde

Figure 3   Mathilde B-Plane Control and Knowledge Uncertainties - Nominal Flyby with Opnav, but without Mathilde Range Data
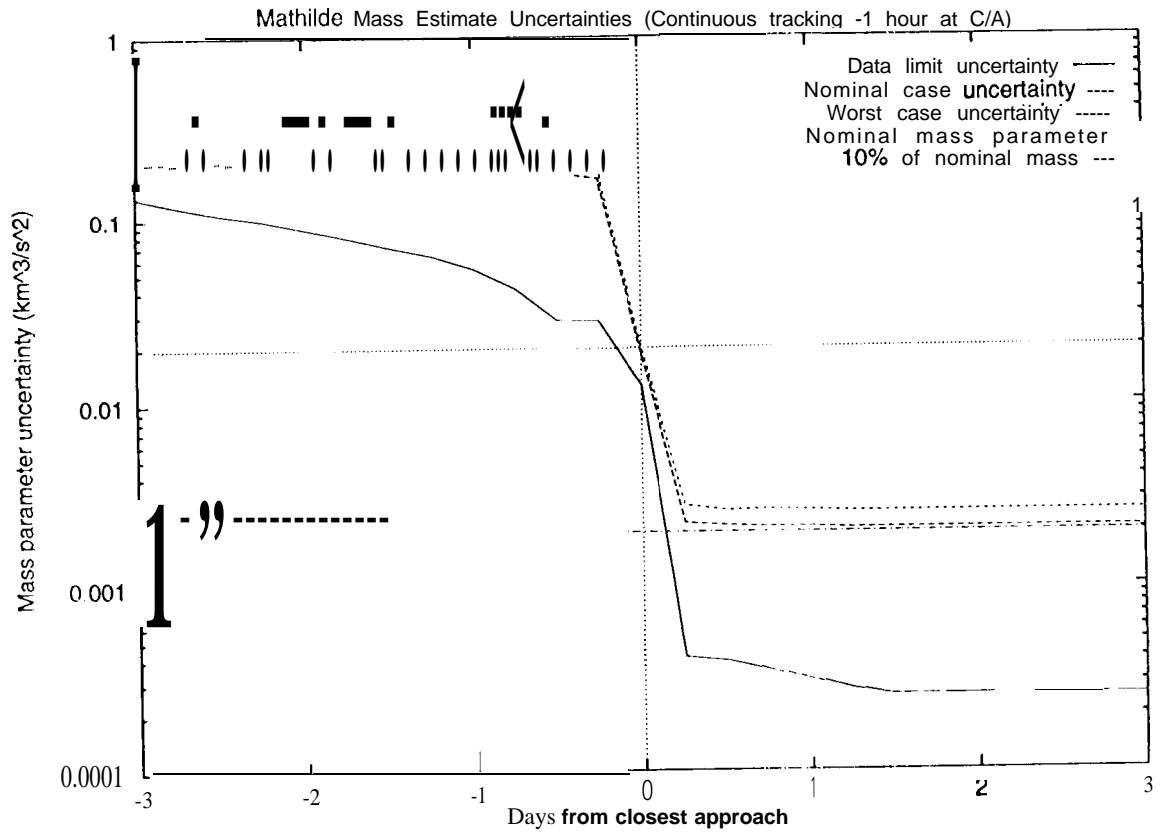
16

Figure 4 Mathilde Mass Estimate Uncertainties - Continous DSN Tracking Minus One Hour Either Side of Closest Approach